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Compact starburst in the central regions of Seyfert galaxies

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Abstract. We have conducted a high-resolution "3D" imaging survey of the CO(1–0), HCN(1–0), and HCO^+(1–0) lines toward the central a few kpc regions of the Seyfert and starburst galaxies in the local universe using the Nobeyama Millimeter Array. We detected luminous HCN(1–0) emissions toward a considerable fraction of these Seyfert galaxies (10 of 12 in our sub-sample), which indicated that some of these Seyfert galaxies, such as NGC 3079, NGC 3227, NGC 4051, NGC 6764, and NGC 7479, are indeed accompanied with compact nuclear starburst, given the tight correlation between the HCN(1–0) luminosity and the star formation rate among star-forming galaxies. However, we suggest that the elevated HCN(1–0) emission from some of these Seyfert galaxies, including NGC 1068, NGC 1097, NGC 5033, and NGC 5194, does not signify the presence of massive starbursts there. This is because these Seyfert nuclei show abnormally high HCN(1–0)/HCO^+(1–0) ratios (2–3), which were never observed in the starburst nuclei in our sample. This could be attributed to the overabundance of HCN molecules in the X-ray dominated regions (XDRs) at the centers of these Seyfert galaxies.

1. HCN as a tracer of star formation in galaxies

A dense molecular medium plays various roles in the vicinity of active galactic nuclei (AGNs). The presence of spatially compact dense and dusty interstellar matter (ISM), which obscures the broad-line regions in the AGNs, is inevitable according to the proposed unified model of Seyfert galaxies. This circumnuclear dense ISM could be a fuel reservoir for active nuclei as well as a site for massive star formation. In fact, a strong enhancement of HCN(1–0) emission with respect to CO has been detected in the prototypical type-2 Seyfert NGC 1068 (Jackson et al. 1993; Tacconi et al. 1994; Helfer & Blitz 1995). Similar enhancements have also been reported in NGC 5194 (Kohno et al. 1996), NGC 1097 (Kohno et al. 2003), and NGC 5033 (Kohno 2005). In these Seyfert nuclei, the HCN(1–0) to CO(1–0) integrated intensity ratios in the brightness temperature scale, $R_{\rm HCN/CO}$, are enhanced up to approximately 0.4–0.6, and the kinematics of the HCN line indicates that this dense molecular medium could be the outer envelope of the obscuring material (Jackson et al. 1993; Tacconi et al. 1994; Kohno et al. 1996).

On the other hand, it is well known that there exists a *tight* and *linear* correlation between HCN(1–0) and FIR luminosities among star-forming galaxies in the local universe (Gao & Solomon 2004). Therefore, one may immediately wonder if massive star formation occurs at the very centers of these Seyfert galaxies. Is HCN emission still a tracer of massive star formation there?

To answer this question, we attempted to find hints from our high-resolution "3D" imaging survey of CO(1–0), HCN(1–0) and HCO^+(1–0) lines toward the central a few kpc regions of the Seyfert and starburst galaxies using the Nobeyama Millimeter Array (Kohno et al. 2001; Kohno 2005). This paper provides a brief summary of the current survey results and their implications on the presence of compact nuclear starbursts in nearby Seyfert galaxies.

2. Nobeyama Millimeter Array Imaging Survey of CO, HCN, and HCO^+ emissions toward Seyfert and starburst galaxies

The majority of the Seyfert sample galaxies belong to the Palomar Northern Seyfert sample (Ho & Ulvestad 2001). Some southern Seyfert galaxies are also included in this sample. The band width of correlator, 1 GHz (Okumura et al. 2000), enables us to detect the HCN(1–0) and HCO^+(1–0) lines simultaneously. This allowed us to make accurate measurements of the ratios of their relative line intensities, i.e., $R_{\mathrm{HCN/HCO^+}}$. Our HCN and HCO^+ cubes have typical resolutions of $\sim 2''$ to $6''$ (or a few 100 pc) and sensitivities of a few mJy beam^{-1} for a $\sim$50 km s^{-1} velocity channel. We detected luminous HCN(1–0) emission toward a considerable fraction of these Seyfert galaxies (10 of 12 Seyfert galaxies in our sub-sample). Among them, we present the molecular line images of the two type-1 Seyfert galaxies NGC 1097 and NGC 7469 in figure 1.

To investigate whether or not these HCN and HCO^+ emissions indeed trace massive star formation in these regions, we computed the ratios, $R_{\mathrm{CO/HCN}}$ and $R_{\mathrm{HCN/HCO^+}}$. Some of the Seyfert galaxies, including NGC 1068, NGC 1097, NGC 5033, and NGC 5194, show enhanced or overluminous HCN emission with respect to the CO and HCO^+ emissions. The $R_{\mathrm{CO/HCN}}$ and $R_{\mathrm{HCN/HCO^+}}$ ratios in these Seyfert galaxies are enhanced up to $\sim$0.2–0.3 and $\sim$2–3, respectively. Crucially, such elevated $R_{\mathrm{HCN/HCO^+}}$ values were *never* observed in our nuclear starburst sample. Given the similar properties of these two molecules (i.e., similar permanent dipole moments and therefore similar critical densities for collisional excitation), the enhancement of $R_{\mathrm{HCN/HCO^+}}$ close to or larger than 2 is unusual. Note that we found no clear correlation between $R_{\mathrm{HCN/CO}}$ and the morphologies of the host galaxies.

One possible explanation for these abnormally luminous HCN emissions with respect to the CO and HCO^+ emissions is the chemistry due to X-ray dominated regions (XDRs) (Maloney et al. 1996), i.e., the overabundance of the HCN molecules in X-ray irradiated dense molecular tori (Lepp & Dalgarno 1996; Meijerink & Spaans 2005). One of the key issues is the high temperature of the molecular clouds in XDRs; in contrast to the photo-dissociation regions (PDRs), where UV photons are blocked at the surface of molecular clouds, high-energy photons can penetrate deep inside molecular clouds. Besides, heating due to photo-ionization in the XDRs is much more efficient than the photo-electric heating in the PDRs. As a consequence, the temperature of the molecular

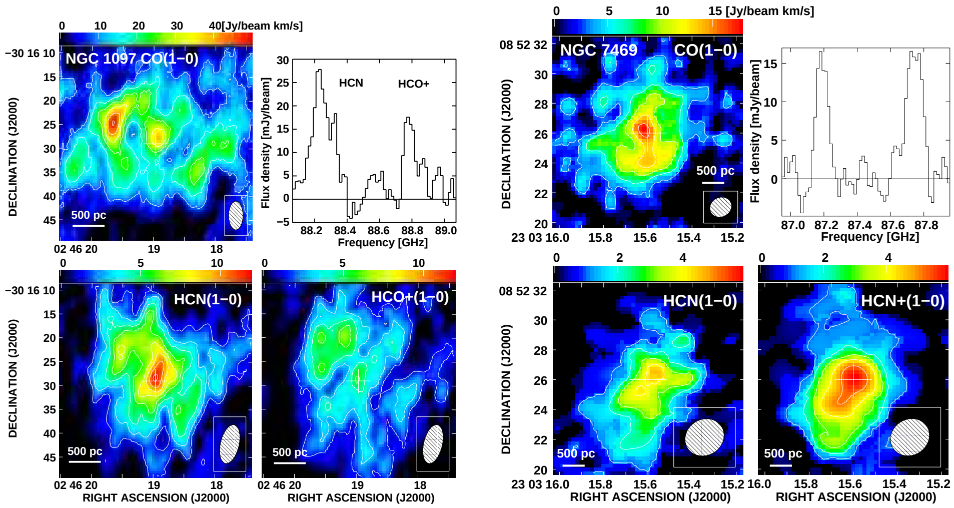

Figure 1. CO(1–0), HCN(1–0), and HCO^+(1–0) images of NGC 1097 (left) and NGC 7469 (right). HCN(1–0) and HCO^+(1–0) spectra at the nuclei positions are also shown. In NGC 1097, the enhancement of HCN(1–0) emission with respect to other emissions is evident; HCN(1–0) emission is dominated by the nucleus, whereas CO(1–0) and HCO^+(1–0) emissions are more luminous in the circumnuclear starburst ring ($r \sim 10''$).

clouds in the XDRs becomes very high as compared with that of the molecular clouds in the PDRs (Maloney 1999; Meijerink & Spaans 2005). In fact, at the center of M 51, a host of low-luminosity AGN (see references in Kohno et al. (1996)), a very high kinetic temperature of the molecular gas has been suggested (Matsushita et al. 1998, 2004). This nucleus is a representative one that shows the overluminous HCN(1–0) emission in our sample ($R_{\mathrm{HCN/HCO^+}} = 2.5 \pm 0.43$).

Our interpretation is also supported by the comparison of our results with these obtained by infrared L-band spectroscopy: a polycyclic aromatic hydrocarbon (PAH) emission at 3.3 μm in the L-band can be considered as a good probe to study nuclear starbursts in Seyfert galaxies (Imanishi 2002, 2003). In table 1, our diagnostic results on the presence of nuclear starburst based on the $R_{\mathrm{HCN/HCO^+}}$ values were compared with those from PAH observations. These two diagnostics provided us with the same conclusions in 6 of 7 Seyfert galaxies. We may need to further investigate the significance of the disagreement in the nucleus of NGC 7469; one possibility is that our spatial resolution is still not sufficient to eliminate the contamination from the circumnuclear starburst regions of NGC 7469.

In summary, the known tight correlation between HCN(1–0) luminosities and SFRs in star-forming galaxies should be treated with caution in the vicinity of active nuclei, provided the high $R_{\mathrm{CO/HCN}}$ and $R_{\mathrm{HCN/HCO^+}}$ values are indeed the signatures of HCN overabundance due to the XDR chemistry. We suggest that *the overluminous HCN(1–0) emission observed in some Seyfert galaxies such as NGC 1068, NGC 1097, NGC 5033, and NGC 5194 does not signify an elevated massive star formation rate there.* Nevetheless, it is still likely that compact nuclear starbursts occur in other Seyfert galaxies in our sample, such as

Table 1. Presence of nuclear starburst in nearby Seyfert galaxies: diagnostics from HCN/HCO^+ ratio and PAH emission

Name	Nuclear starburst?		Ref. for PAH
	HCN/HCO^+	PAH	
NGC 1068	No	No	Imanishi (2002)
NGC 3227	Yes	Yes	Imanishi (2002), Rodriguez-Ardila & Viegas (2003)
NGC 4051	Yes	Yes?	Rodriguez-Ardila & Viegas (2003)
NGC 4388	No	No	Imanishi (2003)
NGC 4501	No	No	Imanishi (2003)
NGC 5033	No	No	Imanishi (2002)
NGC 7469	Yes?	No?	Imanishi & Wada (2004)

NGC 3079, NGC 3227, NGC 4051, NGC 6746, and NGC 7479. This is because the observed $R_{\rm CO/HCN}$ and $R_{\rm HCN/HCO^+}$ values in these galaxies are very similar to those of nuclear starburst galaxies. The comparison of our results with those obtained from L-band PAH spectroscopy also seems to support our conclusions.

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